Gait & Posture 39 (2014) 1005–1010

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Review

Summary measures for clinical gait analysis: A literature review

Veronica Cimolin [a,*], Manuela Galli [a,b]

[a] Department of Electronics, Information and Bioengineering, Politecnico di Milano, Milano, Italy
[b] IRCCS "San Raffaele Pisana", Tosinvest Sanità, Roma, Italy

ARTICLE INFO

Article history:
Received 28 June 2013
Received in revised form 28 January 2014
Accepted 2 February 2014

Keywords:
Gait analysis
Summary measures
Outcome
Locomotion

ABSTRACT

Instrumented 3D-gait analysis (3D-GA) is an important method used to obtain information that is crucial for establishing the level of functional limitation due to pathology, observing its evolution over time and evaluating rehabilitative intervention effects. However, a typical 3D-GA evaluation produces a vast amount of data, and despite its objectivity, its use is complicated, and the data interpretation is difficult. It is even more difficult to obtain an overview on patient cohorts for a comparison. Moreover, there is a growing awareness of the need for a concise index, specifically, a single measure of the 'quality' of a particular gait pattern. Several gait summary measures, which have been used in conjunction with 3D-GA, have been proposed to objectify clinical impression, quantify the degree of gait deviation from normal, stratify the severity of pathology, document the changes in gait patterns over time and evaluate interventions.

Introduction

Three-dimensional instrumented gait analysis (3D-GA) provides comprehensive data on normal and pathological gait, which are useful in clinical practice and scientific purposes because they provide objective information about joint motions (kinematics), time-distance variables (spatio-temporal data), and joint moments and powers (kinetics). It has been widely demonstrated that 3D-GA is an important method that is used to obtain crucial information for the determination of the level of functional limitation due to pathology and for its follow up evaluation over time. Furthermore, it can help to evaluate the rehabilitative intervention aimed at reducing the functional limitation due to pathology. However, a typical 3D-GA evaluation produces a vast amount of data, and despite its objectivity, makes it an instrument that is sometimes complicated to use and difficult to interpret. Specifically, comparative overviews are difficult. There is currently a debate regarding how to best use these data; for example, there is a perspective that the volume of information produced by 3D-GA could be an obstacle for its clinical use. Given the importance of 3D-GA in the management of many populations with movement disorders and because clinical decisions are generally also based on an interpretation of the complex information contained in these data, considerable attention should be directed towards GA data.

Within the last decade, there has been a growing clinical awareness of the need for a concise index, specifically, a single measure of the 'quality' of a particular gait pattern. Several gait summary measures, when used in conjunction with 3D-GA, have been proposed and used to objectify clinical impression, quantify the degree of gait deviation from normal, stratify the severity of pathology, document changes in gait over time and evaluate interventions.

The aim of this review is to summarise the studies on the most important and widespread summary parameters proposed by the literature, focusing on studies proposed for clinical applications and discussing the advantages and limits of these parameters.

Methods

To provide a comprehensive overview on gait summary measures, an electronic literature search was performed within the MEDLINE, CINAHL, EMBASE and Journal Citation Reports databases for articles published in english until December 2012 using the following keywords: locomotion, gait analysis, gait summary measures and biomechanics.

Results

From our research, only studies concerning gait summary measures were considered. The first attempt to define a summary measure was performed in 1979 by Tibarewala and Ganguli [1].

* Corresponding author at: Department of Electronics, Information and Bioengineering, Politecnico di Milano, piazza Leonardo da Vinci 32, 20133, Milano, Italy. Tel.: +39 02 2399 3359; fax.: +39 02 2399 3360.
E-mail address: veronica.cimolin@polimi.it (V. Cimolin).

0966-6362/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.gaitpost.2014.02.001

In healthy adult males, a number of gait curves defined as "normal" gait curves were selected, and a "gait abnormality index" was developed to be used as a quantitative measure of human performance in locomotion, which would be suitable for application in pathological states. Some years later, a computer algorithm was developed to determine the group of electromyographic profiles for the soleus muscle during free speed-level walking in healthy individuals [2]. Next, Kerrigan et al. proposed two indices based on the pattern of the trunk during gait: the vertical displacement of the sacrum during walking [3], which was proposed as an estimation of the overall biomechanical performance of walking, and the biomechanical efficiency quotient (BEQ), which was computed from the average stride length, vertical displacement of the trunk during walking and sacral height during standing [4].

However, after these attempts, which remained isolated, most studies concerning summary measures for 3D-GA and their application in pathological states began in 2000 with the normalcy index [5]. For this reason, we begin our in-depth analysis from Schutte's study. Specifically, for each parameter, beginning from Schutte's study to the most recent study, a brief description is given of the data reduction technique used for the computation, the potential weaknesses/strengths and the main clinical/scientific experiences.

Normalcy index (NI) or gillette gait index (GGI)

The first index that enabled the characterisation of a patient's gait in a global sense with a widespread clinical acceptance is the normalcy index (NI) or gillette gait index (GGI) [5]. It uses multivariate statistical methods to quantify the extent by which a patient's gait deviates from that of an unimpaired control group. The NI is computed using standard multivariate statistical techniques (principal component analysis) applied to 16 3D-GA variables and. in particular, three temporal-spatial parameters (percentage of stance phase, normalised velocity and cadence) and 13 kinematic parameters (mean pelvic tilt, range of pelvic tilt, mean pelvic rotation, minimum hip flexion, range of hip flexion, peak abduction in swing, mean hip rotation in stance, knee flexion at initial contact, time of peak knee flexion, range of knee flexion, peak of dorsiflexion in stance, peak of dorsiflexion in swing and mean foot progression angle). The sum of the square of these 16 independent variables is interpreted as the deviation of the subject's gait from normal. Using this statistical method, it is possible to measure and represent as a single number the deviation of a pathological gait pattern from a normal average profile. Thus, the NI indicates the amount by which a subject's gait deviates from an average normal profile.

The NI appears to be the most extensively validated and commonly cited parameter and is widely used in clinical gait research and practice [6,7]. In particular, its use has been widely validated in cerebral palsy (CP) and idiopathic toe walker populations [5,8]. It has been shown to be effective when used to evaluate the range of pathology present in specific diagnoses, to compare a subject's gait to that of others with the same diagnosis, to track a subject's gait pathology over time, or to examine the effectiveness of an intervention.

Use of the NI to quantify the effects of specific treatments in children with CP has provided evidence that this index represents a valid instrument to quantify the effects of treatments that have a global effect on gait pattern, similar to multilevel orthopaedic surgery [9] and selective dorsal rhizotomy [8]. However, the NI did not exhibit the appropriate specificity and sensitivity when evaluating the effects of targeted interventions, such as AFO [10].

Moreover, the use of the NI in other pathological states, such as in children and adolescents with tumours in the central nervous system (CNS) [11], adults with a diagnosis of central nervous system pathology [12] and adult lower limb amputees [13], have shown that NI could also be used in these pathologies despite some limitations mainly due to the parameter choice [12].

Regarding concerns of the NI limits, a number of limitations have also been observed, and there has been a significant debate about the validity of this method [14]. First, these limitations include the arbitrary, unbalanced, and incomplete nature of the 16 univariate parameters that comprise the index. Their selection was driven largely according to the gait experience in CP but partly by convenience. The presented 16 variables are the 'best effort' of the authors. However, one can conclude that other 'better' sets of variables may be found. Second, the selected parameters included only kinematic variables; it is well known that the inclusion of kinetic variables is useful for a complete gait pattern assessment and in planning intervention. Third, only the characteristic points of the curves are included. These all make up a strong limitation.

According to the computation method, the NI requires an able-bodied gait dataset to establish the means and variance values of the control in each of the variables, and it was found to be strongly sensitive to lab-specific control data. McMulkin and MacWilliams [15] reported a high variability in the values of the NI when different normal populations from different labs were used, when applied to both normal adult individuals and to some patients with CP. They assessed the variation in the calculated NI values with different sets of control data. Differences in the underlying control data generated large differences in the computed NI values for both the pathological and able-bodied subjects. While the NI was shown to be reliable within a single control dataset, it is unknown to what extent its values may differ when using different underlying control sets. Another challenge connected to the NI is the question of whether there is a minimum sample size required in the set of control subjects in order to have a reliable NI tool. If all 16 principle components were used, a minimum of 40 controls were required to achieve an error of less than approximately 20%, and 96 controls were needed for an error less than 10%. Alternatively, using only those principal components that represent 95% of the variance may provide NI values that are more accurate with smaller control sets. However, caution must be taken when using the NI, as even with greater than 40 controls, the differences in the NI score for an individual CP subject may be as high as 150 based solely on the control set.

Hip flexor index (HFI)

Starting from the strong limitation of the NI, which is the inclusion of only the kinematic variables, a new index was developed considering the principal component analysis applied to five kinematic and kinetic variables: maximum pelvic tilt, pelvic tilt range, maximum hip extension in stance, percentage of stance phase in which the final crossover of the hip flexor moment curve from extension to flexion occurs—'timing of crossover'—and peak late stance hip flexor power. A single index number was derived, which accurately describes the overall hip function during gait [16]. Importantly, this does not belong to the same category of GGI (and of the next summary measures) due to its clear focus on a single joint/anatomic level.

The HFI is a valid tool that is used to objectify clinical impressions of a change in hip function and might thereby assist researchers with statistical and outcome analyses of interdependent and redundant gait variables. The HFI measure of post-operative change in hip function corresponded well with the subjective clinical outcome 75% of the time. However, importantly, the main limit of this index is that it is too joint-specific; a change in hip flexor function toward 'normal' may or may not signify a global improvement in the patient's gait. No correlation was made

between the change in score on the HFI and the change in function of the patient. According to these considerations, it is possible to affirm that the HFI can provide clinicians with a simple, reliable, objective and quantitative tool, but it is only suitable for evaluating an intervention at the hip. It has also been applied to assess the effects of specific surgical treatments at the pelvis and the hip joint [17]; no other applications were possible due to the nature of this parameter.

Gait deviation index (GDI)

This recently developed measure is thought to be representative of the overall gait pathology. It is based on the extraction of 15 gait features using the singular value decomposition from the 3D-GA kinematics of the pelvis and hip in three planes, of the knee and ankle on the sagittal plane and of foot progression [14]. It has been verified that 15 features provide a sufficiently accurate approximation to the original gait vector. Applied to a control group, these "gait features" define an averaged, non-pathological gait. The absolute distance between a subject exhibiting gait pathology and the control group is then calculated, providing a measure from which the extent of gait pathology can be determined [14,18]. A GDI of 100 or higher indicates the absence of gait pathology; 10 points below 100 corresponds to one standard deviation away from the healthy group mean. For example, GDI = 75 indicates that the gait of the subject is 2.5 times the standard deviation away from the control mean.

The GDI was moderately correlated with the NI ($r^2 = 0.56$), suggesting that these two parameters are both measures of the same underlying construct, although a large spread at any given level indicates that they measure different aspects of the gait pathology [14].

The face and construct validity of the GDI were investigated both in healthy children and in children with CP [14,19], as well as in adults with spastic CP [20]. The GDI in adults demonstrated similar results in distributional properties as those reported in studies on healthy children and ambulant children with CP [14]. With respect to the NI, there is more experience for the GDI application in other pathologies, such as Batten disease [21], muscular dystrophy [22], lower limb amputees [13] and Parkinson's disease [23]. Although Galli et al. [21] and Thomas et al. [22] did not introduce any considerations regarding GDI, the last two studies found some limitations in this parameter. Kark et al. [13] used the GDI in lower limb amputees, demonstrating that the GDI fails to identify significant differences between the levels of the functional limitation of the intact side. It is also plausible that compensatory strategies of the intact limb in transfemoral and transtibial amputees resulted in similar magnitudes of the overall kinematic deviation, as measured using GDI; in addition, it is possible that a limited sample size prevented this finding from reaching significance. Galli et al. [23] used the GDI for the characterisation of gait in patients with Parkinson's disease, to search for correlations with clinical assessments (unified Parkinson's disease rating scale (UPDRS)), and to evaluate the outcomes of the treatment (levodopa treatment). In the absence of levodopa, GDI was not sufficiently sensitive to measure gait severity in the patients; the reason for this result is twofold. First, although the UPDRS score takes into account the use of walking devices, the GDI is a measure of walking without considering the presence or absence of assistive devices; for this reason, the degree of impairment obtained using these two measures was not similar. Another reason may be associated with the subjective nature of the UPDRS, which might influence the accuracy and precision of the evaluations compared with the quantitative and objective nature of the GDI. However, the GDI has been shown to be a feasible tool to quantify the outcomes of levodopa treatment, even if the gait changes evidenced by the GDI are milder than those evidenced by the clinical evaluations.

Importantly, in comparison to the NI, the GDI has several advantages. The entire variability in kinematic variables across the gait cycle is used rather than a small number of discrete parameters, thereby removing much of the subjectivity in the choice of the parameters. Selection of the parameters for the NI was also specific for children with CP, whereas the GDI appeared to be a more general measure of gait pathology. It was shown that the NI requires a reasonably large number of people in the reference dataset and that values can vary significantly between different reference datasets [15]. In contrast, values of the GDI appeared much less sensitive to differences in the reference data. The GDI proceeds naturally from the analysis of gait features, which provides considerable data compression and a framework for other analytical techniques, such as cluster analysis for gait classification [24].

Gait profile score (GPS) and movement analysis profile (MAP)

Similar to the GDI, GPS is a single index outcome measure that summarises the overall quality of the patient's kinematics. It represents a simpler interpretation of the distance measures underlying the GDI, which results in a modified measure that can be calculated independently of the feature analysis. In addition to a global measure of the overall gait quality, it can be deconstructed to provide the gait variable score (GVS) (an index that measures single gait variable deviation) for nine key relevant kinematic variables (the pelvis and hip in three planes, the knee and ankle on the sagittal plane and the foot progression) [18]. The GPS is generally presented with the nine GVS in a bar chart, thus generating a movement analysis profile (MAP). The MAP describes the magnitude of deviation of the nine individual variables averaged over the gait cycle, thus providing insight into which variables contribute to the increase in GPS. In contrast to the GDI, which uses the first 15 gait features, the GPS uses all the gait features representing the root mean square difference between the patient's data and the average from the reference dataset obtained from all of the relevant kinematic variables for the entire gait cycle.

The GPS was validated against established index measures of gait abnormality and general measures of mobility in children with CP [18]. The authors [18] proposed a rationale for defining a minimal clinically important difference (MCID) for the gait profile score (GPS), which was found to be 1.68, based on an analysis of the differences in the median GPS for children classified at different levels of the functional assessment questionnaire. A strong linear correlation between the median GPS score and the FAQ level was found. The authors remarked that the MCID for the GPS, which reflects the overall quality, might not be sensitive to focal interventions, such as the botulinum toxin, which might have important local effects [25]. However, currently, no experience with the application of GPS to assess the effects of botulinum toxin is present in the literature.

In addition, strong, significant, and positive correlations were found between the GPS and MAP component scores, and the clinicians' ratings of kinematic gait deviation [26], thus providing evidence that these indices have criterion-related validity relative to clinician judgments. The authors proposed that the GPS, particularly its MAP decomposition, might be useful in clinical practice and education as an adjunct to the traditional presentation of complex kinematic data. Acknowledging that kinematic judgments are only a component of the clinical decision-making associated with gait pathology, they proposed that clinicians could use the MAP as an adjunct to traditional gait kinematic presentation. It may also be useful as a measure of both the group and individual outcomes following an intervention or over time. Thus, the fact that the GPS can readily provide MAP GVS components is a potential advantage of the GPS over other single index measures [26].

The GPS has strong face validity because it is based on the RMS difference between gait data for an individual child and the average data from children with no gait pathology. Analysis of the intra-session variability suggests that it is also a reliable measure, and the moderate correlation with NI and a strong correlation between the GPS and the GDI are based on essentially similar measures of difference.

Because the GPS has only recently been developed, there are only a few reports of its use on patients. Thomason et al. [9] and Rutz et al. [27] assessed the outcomes from orthopaedic surgery for children with CP using GPS and MAP. Kark et al. [13] assessed the suitability of GPS and of other gait summary measures (NI and GDI) for use with lower limb amputees. The GPS, similar to the NI, detected significant differences between the levels of amputation on the intact side, while the GDI did not. The differences of the results between GDI and GPS could be a result of the calculation methods. The GDI is calculated against a matrix of able-bodied data, whereas the GPS is calculated against a single column of able-bodied data. This method of calculation may have afforded the GDI a greater variability and may have been responsible for its failure to detect significant differences between the levels of amputation on the intact side. In addition, the MAP was shown to be useful for the elucidation of the underlying causes of gait pathology, which could not be achieved via the other overall gait summary measures [13]. Another element that might justify these different results was obtained using the GPS and GDI and may be due to the GPS being defined as a raw score, whereas the GDI is transformed and scaled.

With respect to the other summary measures, the GPS has some merits. Previous indices derived from the conventional gait model imposed a considerable barrier to the extension of similar techniques to data derived from different gait models or different activities (running, stair climbing, etc); in contrast, the GPS is independent of the feature analysis and can be calculated directly from the data of an individual and the averaged data of people with no gait pathology. Another potential advantage of the GPS is the deconstruction, which is referred to as the MAP. The MAP provides useful insights into which variables contribute to the elevated GPS. The lack of strong correlations of individual GVSs with the GPS and with each other suggests that there is considerably more information contained within the MAP compared to the GPS alone.

One of the limits of the GPS is that, similar to the GDI, no spatio-temporal parameters and kinetics were included in its computation. For the spatio-temporal parameters, it is important to stress that because the gait speed is not correlated with the GPS [18], it is recommended that self-selected walking speed should be reported in addition to the GPS for clinical studies. However, the first attempt to compute the GVS for kinetics was performed by some authors for the ankle dorsi-plantar flexion moment and ankle power [28].

GDI-kinetic

With the exception of HFI, which has the main limitation of being strongly dependent on the pathology, i.e., cerebral palsy, and being focused on a single joint, i.e., the hip, we observed that no global indices presented in the previous sections contained kinetic data in their computation. However, the assessment of gait patterns using only the spatio-temporal parameters and kinematics is not sufficient because they provide a limited evaluation of the patient's gait pattern. The integration of these data with kinetics is crucial for a better investigation of the joint reactions, moments and powers. Thus, it is possible to assess the mechanisms that either control or produce the movement, thereby potentially developing a more comprehensive understanding of motion and providing insight not only into the 'how' (kinematics) but also into the cause (kinetics) of the movement that we observe. To overcome this limitation, the GDI-kinetic was developed [29]. It represents a direct analogy of the GDI, based on joint kinetics rather than kinematics. The method identified 20 gait features of the raw gait kinetic data using singular value decomposition, whose linear combinations of the first 20 gait features produced a 91% faithful reconstruction of the data. Concurrent and face validity for the GDI-kinetic are presented via comparisons with the GDI, gillette functional assessment questionnaire walking scale (FAQ), and topographic classifications within the diagnosis of CP. The GDI-kinetic and GDI are linearly related, but are not strongly correlated, indicating that for any given level of GDI-kinetic, there can be a wide variety of kinematic patterns and vice versa, suggesting that each index measures a different aspect of gait pathology. Similar to the GDI, the GDI-kinetic scales with FAQ level distinguish levels from one another. The GDI-kinetic also scales with respect to the clinical involvement based on topographic CP classification in hemiplegia types I–IV, diplegia, triplegia, and quadriplegia. Interestingly, in hemiplegia, the unaffected limb exhibits lower GDI-kinetic scores than the affected side, indicating that compensations in the unaffected limb result in greater deviations from normal gait than those observed in the affected limb [29]. The GDI-kinetic was able to complement the GDI with a more comprehensive measure of gait pathology, including not only kinematics but also kinetics. However, to the best of our knowledge, there are currently no other studies and applications of this index available in the literature.

Other summary measures

Other summary measures have been proposed in the literature, but their application was limited and they were not widely clinically applied [6,30,31].

Tingley et al. [30] used a data reduction technique by combining two concepts. The first concept involves having an overall 'score' for the gait patterns produced from an analysis, which evaluates the pattern of multiple curves simultaneously; the second concept is the use of 'interpretable functions' as an alternative to principal component analysis, which is used for most of the previously presented parameters. Variation from the mean can then be summarised with a one-dimensional statistic, which is represented as a squared distance from the population mean. Percentiles of this one-dimensional index can be calculated, enabling the classification of a child as normal, unusual or abnormal. A key feature of this analysis is that it is applied across multiple joint angle curves and their derivatives, thus providing a measure that takes into account the interactions between the curves as well as their individual characteristics. The authors applied this index to a group of developing children and to a group of children who were born prematurely, thereby demonstrating good discrimination ability.

Barton et al. [31] used the power of self-organising artificial neural networks or self-organising map (SOM) in order to visualise complex gait patterns in the form of single curves. The SOM operates by converging gait data to stem-patterns, which are arranged on a relational map in the context of the total data space presented to the SOM during training. This method enables the identification of existing gait patterns and opens up the possibility of defining new gait patterns, which are otherwise difficult to identify in the multi-dimensional data space. This method provides repeatable dimensionality reduction with a resolution that can be controlled by careful selection of the input data. The multi-dimensional ranking of subjects is possible both cross-sectionally and longitudinally. The authors affirmed that the proposed method might provide an alternative representation of gait analysis results, which can cope with the complexity of the data and can help to make decision-making more repeatable and more objective. This method was used to identify differences in lower extremity coordination between different types of foot orthoses and to assess the gait quality in a group of patients with various gait problems [6].

Conclusions

The aim of this review paper is to provide an overview of the most frequent gait summary measures that have a clinical application, which were computed starting from 3D-GA. For all indices, after a brief presentation of the calculation methods and the applications on pathological states, their advantages and limitations were discussed.

A discrete number of papers was found on summary measures, but we observed that most of these studies were articles describing the origin and construction of these parameters; only a small number of studies presented a practical and clinical use.

Importantly, because all of the included parameters are derived from 3D-GA data, they are susceptible to the same sources of error that are inherent to clinical 3D-GA (e.g., soft tissue artefact, marker misplacement). However, the principal component method, which is used to derive most of these parameters, assigns weighting factors that are inversely proportional to the amount of variation exhibited by each gait measure in the unimpaired population. Thus, this method provides a rational and objective scheme by which the most consistently measured gait parameters have the greatest influence. This ensures that neither natural variation nor experimental errors contribute excessively to the indices computation.

According to the 3D-GA report, which is generally used in clinical gait analysis laboratories, the proposed summary measures considered general parameters or plots of the pelvis and hip in three planes, the knee only the sagittal plane (because the coronal plane is prone to artefact (i.e., cross-talk from poor knee axis alignment) and the transverse plane of less clinical relevance in most laboratories) and the ankle in the sagittal plane (for reasons of clinical utility and practicality because few laboratories regularly collect three-dimensional hind foot data required to compute coronal and transverse plane ankle rotations). This represents a limitation in case of need for a deeper analysis of the knee or foot.

In addition, all of the proposed indices focused on the task of level ground walking. If the activity of interest were stair climbing, rising from a chair or jumping, then a completely different set of variables would likely be warranted. In addition, the NI and GDI are based on the identification of gait features, but although the authors have made the gait features derived from this analysis available for use, this does limit the potential for this technique to be expanded into other applications. Deriving a similar index for a new biomechanical model based on a different marker set, incorporating functional calibration, or including more complex modelling of the foot, for example, would be a considerable undertaking. According to this consideration, while the NI and GDI are derived from the conventional gait model, they impose a considerable barrier to extending similar techniques to data from different gait models or different activities (running, stair climbing, etc). In contrast, the GPS has the advantage of being independent of the feature analysis and can be directly calculated from the data of an individual and the averaged data of people with no gait pathology. The main limitations of the proposed indices, with the exception of the GDI-kinetic, are the exclusion of kinetic and EMG data, which are instead crucial in the complete assessment of the gait pattern. The inclusion of kinetics enables the assessment of the mechanisms that produce movement; in addition, dynamic EMG provides the timing and action of muscles, which provides a comprehensive snapshot of the subject's walking pattern and an empirical basis for identifying the functional cause of a gait abnormality. In addition, it is important to underline that, with the exception of the NI, the other summary measures do not include velocity in their computation. Because it is well known that walking speed affects many fundamental elements of gait, such as kinematic parameters in the sagittal, coronal, and transverse planes, kinetic data (ground reaction force, moment, and power), EMG signals and spatio-temporal parameters, we suspect that the presented summary measures are dependent on walking speed. From these considerations, efforts should be addressed at developing a new summary measure that can be deconstructed into single gait variable deviations, such as the GPS, but also including spatio-temporal parameters, kinetic and EMG data (Fig. 1).

In general, the studies included in the present paper demonstrate how summary measures could represent a useful tool mainly in clinical settings to objectively quantify the degree of gait

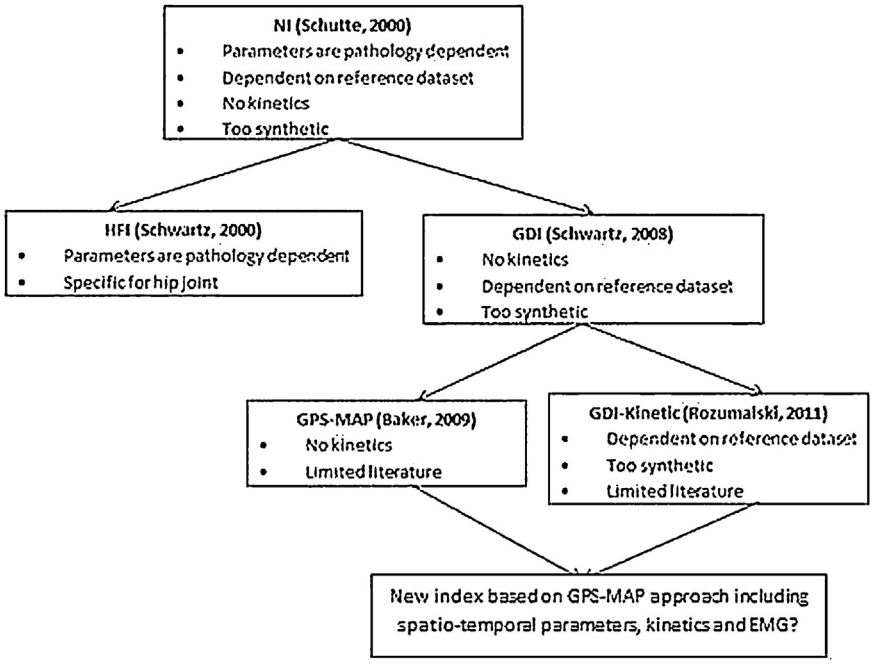

Fig. 1. Summary of the limits of the discussed global parameters and a proposal for a new index.

deviation from normality, stratify severity and to quantify the effects of rehabilitative treatments. In contrast, they may have some limitations, suggesting their use by biomechanical experts.

In our opinion, for clinical applications, summary measures should always be used in conjunction with all of the information (spatio-temporal parameters, kinematics, kinetics and EMG data) represented in the 3D-GA report. The simple use of summary measures alone provides no indication of the interaction among joints and of the interaction among the movement planes, information about the interaction among kinematics, kinetics and EMG, and the assessment of copying response, which can be obtained only when considering all of the 3D-GA graphs. Another limitation of the summary measures to quantify the gait patterns of a subject or the effects of a treatment is that favourable and adverse changes might be masked when using a single number.

Conflict of interest

Nothing to declare.

References

[1] Tibarewala DN, Ganguli S. Use of a gait abnormality index for locomotion efficiency evaluation. J Biomed Eng 1979;1(4):263–4.
[2] Bogey RA, Barnes LA, Perry J. A computer algorithm for defining the group electromyographic profile from individual gait profiles. Arch Phys Med Rehabil 1993;74:286–91.
[3] Kerrigan DC, Viramontes BE, Corcoran PJ, LaRaia PJ. Measured versus predicted vertical displacement of the sacrum during gait as a tool to measure biomechanical gait performance. Am J Phys Med Rehabil 1995;74:3–8.
[4] Kerrigan DC, Thirunarayan MA, Sheffler LR, Ribaudo TA, Corcoran PJA. Tool to assess biomechanical gait efficiency; a preliminary clinical study. Am J Phys Med Rehabil 1996;75:3–8.
[5] Schutte LM, Narayanan U, Stout JL, Selber P, Gage JR, Schwartz MH. An index for quantifying deviations from normal gait. Gait Posture 2000;11:25–31.
[6] Barton G, Lisboa P, Lees A, Attfield S. Gait quality assessment using self-organising artificial neural networks. Gait Posture 2007;25:374–9.
[7] Hillman SJ, Hazlewood ME, Schwartz MH, van der Linden ML, Robb JE. Correlation of the Edinburgh Gait Score with the Gillette Gait Index, the Gillette Functional Assessment Questionnaire, and dimensionless speed. J Pediatr Orthop 2007;27:7–11.
[8] Trost JP, Schwartz MH, Krach LE, Dunn ME, Novacheck TF. Comprehensive short-term outcome assessment of selective dorsal rhizotomy. Dev Med Child Neurol 2008;50:765–71.
[9] Thomason P, Baker R, Dodd K, Taylor N, Selber P, Wolfe R, et al. Single-event multilevel surgery in children with spastic diplegia: a pilot randomized controlled trial. J Bone Joint Surg Am 2011;93:451–60.
[10] Brehm MA, Harlaar J, Schwartz M. Effect of ankle-foot orthoses on walking efficiency and gait in children with cerebral palsy. J Rehabil Med 2008;40:529–34.
[11] Syczewska M, Dembowska-Bagińska B, Perek-Polnik M, Kalinowska M, Perek D. Gait pathology assessed with gillette gait index in patients after CNS tumour treatment. Gait Posture 2010;32:358–62.
[12] Cretual A, Bervet K, Ballaz L. Gillette gait index in adults. Gait Posture 2010;32:307–10.
[13] Kark L, Vickers D, McIntosh A, Simmons A. Use of gait summary measures with lower limb amputees. Gait Posture 2012;35:238–43.
[14] Schwartz MH, Novacheck TF, Trost J. A tool for quantifying hip flexor function during gait. Gait Posture 2000;12:122–7.
[15] McMulkin ML, MacWilliams BA. Intersite variations of the gillette gait index. Gait Posture 2008;28:483–7.
[16] Schwartz MH, Rozumalski A. The gait deviation index: a new comprehensive index of gait pathology. Gait Posture 2008;28:351–7.
[17] Novacheck TF, Trost J, Schwartz MH. Intramuscular psoas lengthening improves dynamic hip function in children with cerebral palsy. J Pediatr Orthop 2002;22:158–64.
[18] Baker R, McGinley JL, Schwartz MH, Beynon S, Rozumalski A, Graham HK, et al. The gait profile score and movement analysis profile. Gait Posture 2009;30:265–9.
[19] Cimolin V, Galli M, Vimercati SL, Albertini G. Use of the gait deviation index for the assessment of gastrocnemius fascia lengthening in children with cerebral palsy. Res Dev Disabil 2011;32:377–81.
[20] Maanum G, Jahnsen R, Stanghelle JK, Sandvik L, Larsen KL, Keller A. Face and construct validity of the Gait Deviation Index in adults with spastic cerebral palsy. J Rehabil Med 2012;44(3):272–5.
[21] Galli M, Ferrario D, Patti P, Freedland R, Cimolin V, Gavin M, et al. The use of 3d motion analysis in a patient with an a typical juvenile neuronal ceroid lipofuscinoses phenotype with CLN1 mutation and deficient PPT activity. J Dev Phys Disabil 2012;24(2):155–65.
[22] Sienko Thomas S, Buckon CE, Nicorici A, Bagley A, McDonald CM, Sussman MD. Classification of the gait patterns of boys with Duchenne muscular dystrophy and their relationship to function. J Child Neurol 2010;25:1103–9.
[23] Galli M, Cimolin V, De Pandis MF, Schwartz MH, Albertini G. Use of the gait deviation index for the evaluation of patients with Parkinson's disease. J Mot Behav 2012;44:161–7.
[24] Rozumalski A, Schwartz M. Natural crouch gait classification in relation to clinical parameters. Gait Posture 2008;28S:S1–47.
[25] Baker R, McGinley JL, Schwartz M, Thomason P, Rodda J, Graham HK. The minimal clinically important difference for the gait profile score. Gait Posture 2012;35:612–5.
[26] Beynon S, McGinley JL, Dobson F, Baker R. Correlations of the gait profile score and the movement analysis profile relative to clinical judgments. Gait Posture 2010;32:129–32.
[27] Rutz E, Baker R, Tirosh O, Romkes J, Haase C, Brunner R. Tibialis anterior tendon shortening in combination with Achilles tendon lengthening in spastic equinus in cerebral palsy. Gait Posture 2011;33:152–7.
[28] Firth GB, Passmore E, Sangeux M, Thomason P, Rodda J, Donath S, et al. Multilevel surgery for equinus gait in children with spastic diplegic cerebral palsy: medium-term follow-up with gait analysis. J Bone Joint Surg Am 2013;95:931–8.
[29] Rozumalski A, Schwartz MH. The GDI-kinetic: a new index for quantifying kinetic deviations from normal gait. Gait Posture 2011;33:730–2.
[30] Tingley M, Wilson C, Biden E, Knight WR. An index to quantify normality of gait in young children. Gait Posture 2002;16:149–58.
[31] Barton, Lees, Lisboa, Attfield. Visualisation of gait data with Kohonen self-organising neural maps. Gait Posture 2006;24:46–53.